FLIGHT EXPERIENCE OF THE BIRD ONBOARD NAVIGATION SYSTEM

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ABSTRACT *– The German BIRD small satellite was launched on October 22, 2001, carrying an elaborate GPS-based Onboard Navigation System (ONS) which provides precise real-time onboard orbit determination as well as orbit and event prediction capabilities. The ONS data are provided in real-time to the Attitude Control System to allow for a nadir pointing of the spacecraft during image sessions as well as for the geocoding of BIRD sensor images on-the-flight. Based on the first five days of ONS operations, the status of the system is described and preliminary analysis results are presented. Emphasis is given to the performance of the GPS receiver as well as the ONS orbit determination and prediction capabilities. The results for the GPS accuracy performance indicate measurement errors of 10 m (rms) for position and of 0.4 m/s (rms) for velocity. Using a dynamical filtering of the GPS measurements, the ONS arrives at a position accuracy of 5 m (rms) and 0.006 m/s (rms) for velocity. The latter is important for orbit prediction and allows to forecast the position over two hours to better than 110 m. The system has reached its operational status by now and the results achieved so far supersede the expectations.*

KEYWORDS: BIRD, autonomous navigation, orbit determination, GPS

INTRODUCTION

The BIRD (Bi-spectral Infra-Red Detection) small satellite, developed by the German Aerospace Center (DLR), has successfully been launched on October 22, 2001 aboard an Indian PSLV rocket. The BIRD major mission objectives comprise the test of a new generation of infrared array sensors as well as the detection and scientific investigation of hot spots, like forest fires, or volcanic activities [1]. As a technology and scientific satellite, BIRD is equipped with a GPS-based autonomous navigation system which provides real-time onboard orbit determination as well as orbit and event prediction capabilities.

The Onboard Navigation System (ONS) supports the BIRD Attitude Control System (ACS) with real-time attitude information to allow for a nadir pointing of the spacecraft during image sessions and data downlinks. In addition, precise ONS position data are merged onboard the spacecraft with BIRD image sensor data, thus enabling a geocoding of satellite images on-the-flight. Furthermore, the ONS derives precise timing information from the GPS receiver for a proper synchronization of the BIRD onboard clock based on the measured bias and drift rate. Finally, NORAD twoline elements are autonomously generated onboard from GPS data, to be downlinked via telemetry for antenna pointing and pass scheduling.

THE BIRD MISSION

Launcher Sequence

The PSLV-C3 rocket launched on October 22, 2001 at 04:53 UTC from India's SHAR Center complex at Sriharikota, located on the east coast of the nation near the Bay of Bengal. The Indian Technology Experiment Satellite (TES) was the major payload which was, together with the German BIRD spacecraft, injected into a 568 km altitude sun-synchronous orbit.

Bird Injection Orbit and Early Operations

Separation of the BIRD satellite was recorded at 2001/10/22 05:09:49.44 UTC, about 17 minutes into a nominal PSLV flight. The rotation of the BIRD satellite at separation was about 5º/s, which was subsequently stopped using a set of four reaction wheels which oriented the spacecraft with its -*z*-axis towards the Sun. At DLR's German Space Operations Center (GSOC) at Oberpaffenhofen, where the BIRD operations are conducted, the first signal of the BIRD spacecraft was recorded at 06:03 UTC, about 53 minutes past separation. At about 09:15 UTC, the spacecraft's solar arrays were successfully deployed.

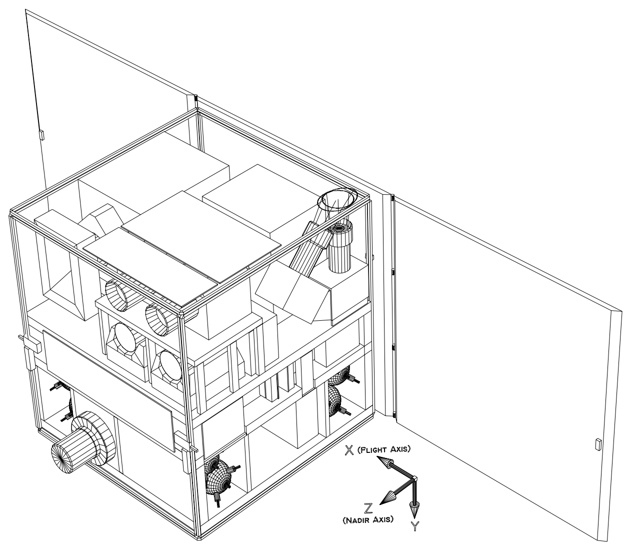

Fig. 1 The BIRD spacecraft in flight configuration

The achieved and nominal orbit injection elements are given in Tab. 1. As can be seen, the performance of the PSLV was superb, which contributed to the smooth early operations, since the reported time and angle offsets at the ground stations were only marginal. The achieved sun-synchronous orbit has a local equator crossing time of 10:30 which corresponds to a shadow duration of 35 minutes per orbital period.

Table 1 BIRD achieved and nominal osculating injection elements, referring to a true-of-date (TOD) reference system. The epoch of the given elements is close to separation.

BIRD orbit elements	Achieved	Nominal	Difference	[σ]
Semi-major axis [km]	6945.857	6944.956	0.901	0.08
Eccentricity []	0.001299	0.000482	0.00082	-
Inclination [º]	97.772	97.678	0.094	1.4
Right ascension of ascending node [º]	8.177	8.197	-0.020	-
Argument of latitude [º]	210.026	209.667	0.002	-

Spacecraft Description and Payload System

The BIRD spacecraft weighs a total of 92 kg (including 26 kg payload) and consists of a cubic structure (see Fig. 1) measuring 55x62x65 cm^3 (WxDxH). The spacecraft structure is divided into a payload platform with the optical camera and the infrared sensors, an electronics segment as well as a service segment, which holds the batteries, the reaction wheels, the gyros, and the GPS receiver. Two self-deployable and one body-fixed solar array provide an average power of 60 W throughout a day, which is buffered in batteries to support a peak power consumption of 210 W.

BIRD carries a total of four imaging sensors operating at visible and infrared wavelengths. Among these, the Medium Wave Infrared Sensor (MWIR, 3.5-4.3 μm) and the Long Wave Infrared Sensor (LWIR, 8.5-9.3 μm) provide frame images with a ground sample distance of 185 m. WAOSS (Wide Angle Optoelectronic Stereo Scanner) is a 3-line CCD stereo camera, which maps the Earth at a pixel size of 185 m from a 560 km altitude. In addition, the panchromatic array camera HORUS has been added to the payload segment to provide a 6 m ground pixel size at a ground footprint size of 4.5 km.

Attitude Control System

The Attitude Control System (ACS) comprises two star sensors and a 3-axis laser gyro system for fine pointing as well as Sun sensors and a magnetometer for coarse attitude determination. Control torques can be generated by four reaction wheels and three magnetic coils. In addition, orbit-related information is provided by the GPS-based Onboard Navigation System, which is described in detail in the sequel.

Aside from safe-mode functions, the ACS is designed for a Sun-pointing mode and an Earth-pointing mode. During most of the day, the spacecraft will be Sun-pointing to recharge the battery between subsequent camera data takes. For imaging sessions as well as for the data downlink, that both last for typically 10-15 minutes, the spacecraft is temporarily oriented towards nadir and reoriented thereafter.

DESCRIPTION OF THE BIRD ONBOARD NAVIGATION SYSTEM

System Objectives

From a functional point of view, the ONS is part of the BIRD ACS, since its main objective is to provide the ACS with position information, which is required for the nadir pointing of the payload sensors and the S-band high-gain antenna. However, as a technology demonstrator the ONS objectives are far more advanced and comprise the

- Provision of the ACS with orbit information, that is required for the Earth-pointing of the spacecraft
- Provision of Earth-fixed position information for the geocoding of the BIRD image data
- Support of the time synchronization of the spacecraft clock using the GPS One-Pulse-Per-Second
- Provision of onboard generated Twoline elements with the Realtime-Twoline Generator (RTG) to the experimental ground station on an experimental basis.

The ONS Orbit Determination Conception

The ONS force model applies the JGM-3 coefficients to model the Earth's gravity field, that is completely taken into account up to order and degree of 10. Considering the measurement update periods of 30 s and prediction periods of 30 minutes, accelerations due to drag, solar radiation pressure, as well as gravitational perturbations from the Sun and the Moon may safely be neglected.

GPS position fixes are treated as pseudo measurements within the ONS orbit determination. To that end, a transformation from the WGS84 to the TOD system (internally used as well as for the ACS interface) is required, that considers, for sake of simplicity, robustness, and computational efficiency, only the sidereal rotation matrix, assuming UT1=UTC.

Within the orbit determination, GPS position fixes are processed as statistically independent pseudo-measurements, making use of an extended Kalman filter. The a priori state vector is based on GPS position and velocity measurements, while the GPS velocity measurements are not applied as measurements within the filter due to their inferior accuracy. The time update phase comprises with the propagation of the previous estimate, the computation of the state transition matrix and the state covariance matrix. To account for an imperfect modeling of the satellite dynamics, the covariance matrix is increased in each step by a constant and diagonal state noise matrix. The measurement update assumes uncorrelated position coordinates (x, y, z), that are treated sequentially, in which case the Kalman gain matrix collapses to a six-dimensional vector and a matrix inversion is avoided.

The ONS employs an advanced numerical integration scheme (RK4R), that extends the common Runge-Kutta 4th order algorithm (RK4) by a Richardson extrapolation and a Hermite interpolation [2]. The algorithm comprises two elementary RK4 step sizes of length h, and can be shown to be effectively of 5th order with 6 function calls per h. The Hermite interpolation of the spacecraft position allows for an efficient provision of dense position output, that is required for the high-frequency geocoding of the payload images. Step sizes depend on the measurement times and may vary between 30 and 65 s [3]. In view of the moderate step sizes, the state transition matrix is computed based on a Keplerian approximation.

GEM-S RECEIVER DESCRIPTION AND OPERATIONAL EXPERIENCE

GPS Receiver Hardware

The BIRD Onboard Navigation System makes use of a GPS Embedded Module III (GEM-S) by Rockwell Collins [4] to obtain GPS position fixes for real-time orbit determination. GEM-S is a five channel L1 SPS C/A- and P-code receiver, that has earlier been flown on several Space Shuttle missions.

The primary power input to GEM-S is provided through ±5 V DC and approximately 6.4 W are required for nominal operations. Although GEM-S supports a MIL-STD Dual Port RAM interface (DPRAM) as primary interface for GEM-S operations, the operations entirely relies on the RS422 interface due to its simplicity. In addition to the data interface, a One-Pulse-Per-Second (1PPS) signal is issued by the receiver, that is used for synchronization of the BIRD onboard clock.

The receiver operations are highly complicated, since the serial GEM-S interface does not fully support the initialization for space operations. Hence a sequence of memory change commands have to be applied to directly access the receiver's internal memory. These commands must be properly time-tagged relative to a GEM-S hardware reset, that can only be performed using time-tagged commands. To overcome the complex space initialization, extensive use has been made of high-level macro commands, that generate native GEM-S commands onboard and utilize the onboard availability of SGP4 mean elements to compute the instantaneous position and velocity.

GPS Operations Experience

The initialization of the GPS receiver was among the primary objectives on 2001/10/24, when the first ONS activities were scheduled. Following the switching on of the GPS receiver, a series of commands were issued to activate and deactivate particular GEM-S messages types, which confirmed the proper functioning of the GEM-S related TM/TC interface. Without any further intervention from ground, the GEM-S had, 19 minutes after its activation, obtained frame lock in one of its channels, which allowed to set the proper date and time. About 26 minutes after the cold start, the receiver had collected a complete GPS almanac without any command support.

Following its first cold start initialization, the GEM-S achieved its full operational tracking state about 6 minutes later, thus significantly exceeding the Time-To-First-Fix (TTFF) found during HWIL tests (indicating a TTFF of 2 minutes). Since then two hot start initializations (during nominal operations) were performed with TTFF's of 45 s and 180 s as well as one warm start (no GPS ephemeris available) with 291 s.

Of utmost importance for the orbit determination performance is the availability of GPS position fixes, which serve as pseudo-measurements for the Kalman filter. Since the orbit determination thread is invoked every 30 s and checks for available valid measurements within its current cycle, the number of measurement updates is a good indicator for the tracking performance of the GEM-S receiver. Since its proper initialization, about 6300 Kalman filter updates have been performed with about 6000 measurement updates, which demonstrates that valid GPS data are available about 95% of the time.

To assess the tracking quality of the GEM-S position and velocity data, a 5 hour arc of GEM-S position fixes, sampled at 30 s, has been processed on-ground with a precision orbit determination software. Thus a reference trajectory has been established, which has subsequently been used to compute the GEM-S position and velocity residuals. The data residuals, projected onto a radial, east, and north oriented triad are depicted in Fig. 2. In the position residuals, pronounced spikes are visible, reaching up to 300 m, that were already detected during HWIL simulations and which are related to the rise or set of GPS satellites in the local horizon of the GPS antenna. In part, those errors arise from an improper treatment of ionospheric errors for space applications within the GEM-S. Another contribution to the observed spikes is the degraded radial position accuracy (see Fig 2), resulting from a poor observation geometry when GPS satellites are close to the GPS antenna's local horizon. This problem is related to the low number of tracking channels provided by the GEM-S.

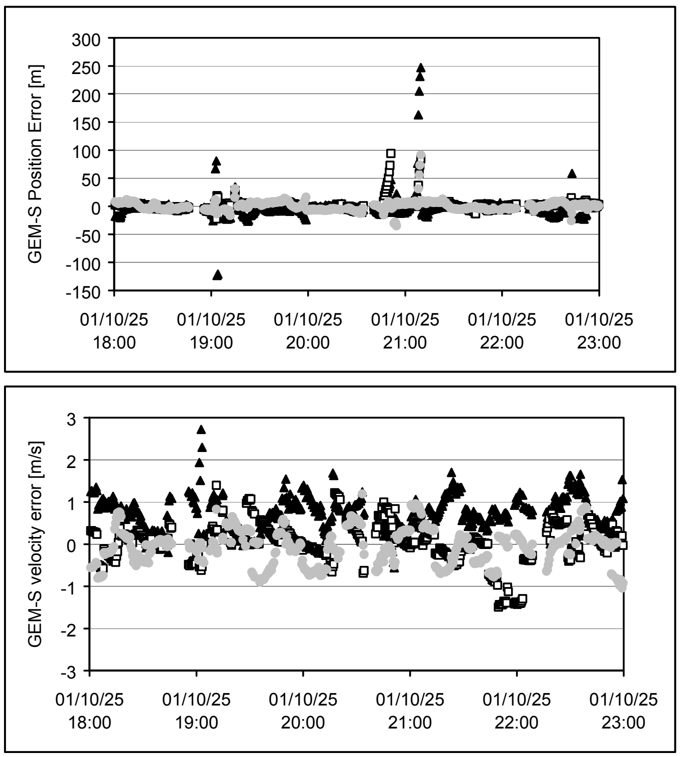

Fig. 2 Position residuals (above) and velocity residuals (below) of GEM-S fixes for a representative period on 2001/10/25. Back triangles denote the radial components, open rectangles indicate East components and gray circles show North components.

None of the residual components in Fig. 2 shows a significant deviation from zero mean, hence there are no hints for any systematic errors in the receivers computation of position and velocity fixes. The quality of the GEM-S position fixes is comparable to other GPS receivers, e.g. JPL's Blackjack receiver on the Champ satellite. When eliminating obvious outliers with residuals exceeding 100 m and 3 m/s, the noise of the GEM-S position and velocity fixes has been determined as 10 m and 0.41 m/s, respectively.

OPERATIONAL EXPERIENCE FROM THE ONBOARD NAVIGATION SYSTEM

Orbit Determination Initialization

On October 24, a first initialization of the ONS orbit determination has been performed, that confirmed the basic functioning of the thread. A proper initialization of the thread had, however, to wait until October 31, when the first time synchronization of the satellite board computer (SBC) clock was performed, that synchronized to the millisecond level the onboard UTC time to the UTC time, as derived by the GPS receiver. The orbit determination initialization has been performed using GPS position and velocity data, thus no command parameters where required for orbit determination initialization, demonstrating the high level of board autonomy for ease of ground operations.

Upon using predefined optimal filter and orbit determination parameters, the ONS orbit determination received the first set of GPS data at 2001/10/31 14:18 UTC and achieved a steady-state position standard deviation of 25 m at about 1.5 orbital periods thereafter. To assess the quality of the ONS onboard orbit determination solution, a reference trajectory has been established, based on GSOC's precise orbit determination tool. The data arc applied for the reference solutions extended the monitoring arc by one orbit revolution before and one orbit revolution after the monitoring arc.

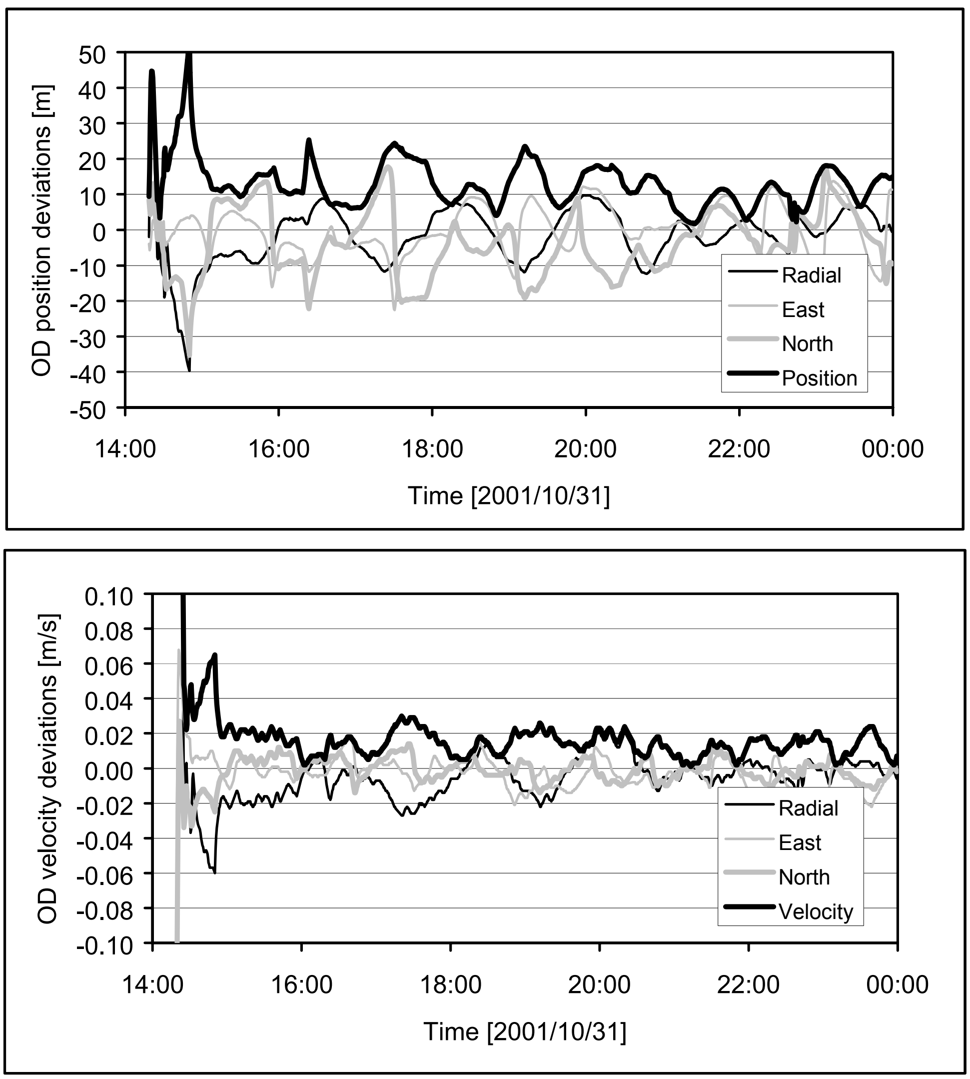

Fig. 3 Position residuals (above) and velocity residuals (below) of the ONS orbit determination solution after initialization on 2001/10/31.

The results are illustrated in Fig. 3, where the position and velocity deviations of the onboard determined solution from the reference trajectory are shown over an arc of more than 6 orbital periods. Following the filter convergence, the position and velocity residuals stay essentially below 20 m and 2 cm/s. Upon filter convergence, the orbit determination accuracy for the position is 5.3 m (rms) and 6.3 mm/s (rms) for velocity. Thus the Kalman filtering improves the position accuracy by a factor of 2 and, most essentially for orbit prediction, reduces the velocity errors by more than a factor of 50.

To analyze the ONS orbit determination performance more closely, the established reference orbit has been employed to map the ONS orbit determination positions to an orbital reference system. As a result, a sequence of height, along-track and cross-track components during the prediction arc have been obtained. The ONS trajectory relative to the reference orbit is depicted in Fig. 4, where planes perpendicular to the along-track and the cross-track direction have been chosen, respectively. While the height and cross-track errors (Fig. 4 left) show no obvious systematic pattern, the height and cross-track errors (Fig. 4 right) partially exhibit an ellipsoidal pattern. Two major ellipses are discernible with a semi-major axis of about 30 m and a semi-minor axis of 8 m. The ellipse to the right is shifted from the origin in along-track direction by about 10 m. This is attributed to a still not fully converged filter solution, since this ellipse is traversed first.

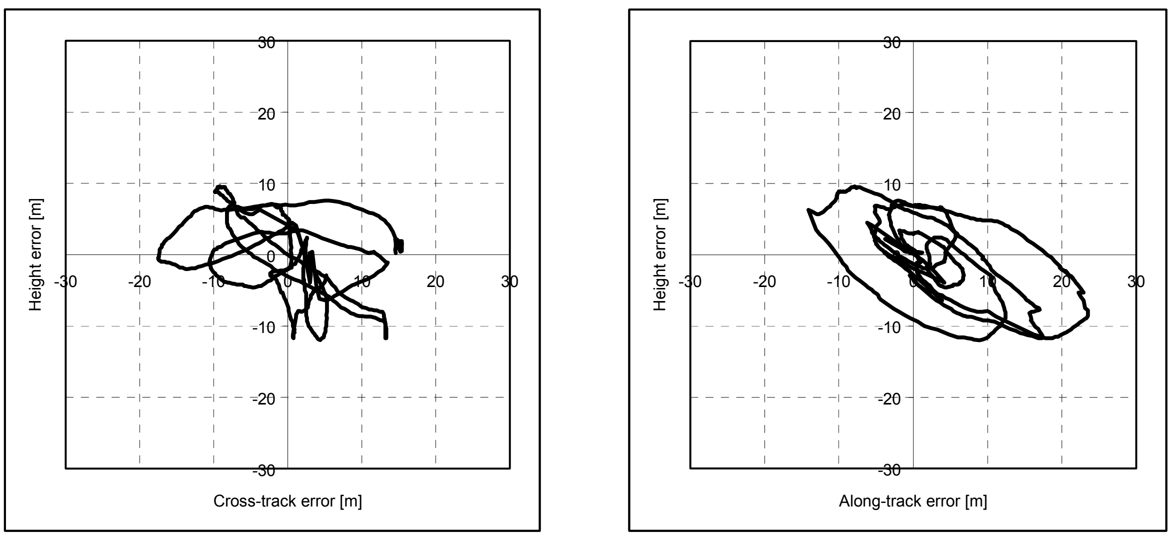

Fig. 4 Position errors of the ONS orbit determination solution w.r.t. to a precise reference trajectory. Relative positions have been projected onto a plane perpendicular to the along-track (left) and the cross-track direction (right).

Orbit Propagation Performance

Following its initialization on October 31, the orbit determination process continued to perform measurement updates every 30 s. Thus no orbit prediction arcs beyond one minute were available. This situation changed abruptly on November 1, 2001 at 12:00 UTC, when the GEM-S receiver suddenly lost track of all satellites. Only at 13:51 UTC on the same day, the GEM-S was back in its nominal tracking mode without any ground intervention. This event thus led to a continuous orbit prediction arc of about 110 minutes, slightly exceeding one orbit revolution, and has been applied to analyze the orbit prediction performance of the ONS.

To monitor the GPS measurement and ONS filter solution residuals over the orbit prediction arc, a reference trajectory has been established. To that end, a GPS data arc from 8:30–17:30 UTC on 2001/11/01 has been selected to estimate the epoch state vector using a precise batch least-squares orbit determination software on-ground. Based on the estimated epoch state vector a reference trajectory was generated and the ONS orbit determination performance was monitored (see Fig. 5) over an arc from 10:00–16:00 UTC on 2001/11/01, thus covering a total of four orbital periods.

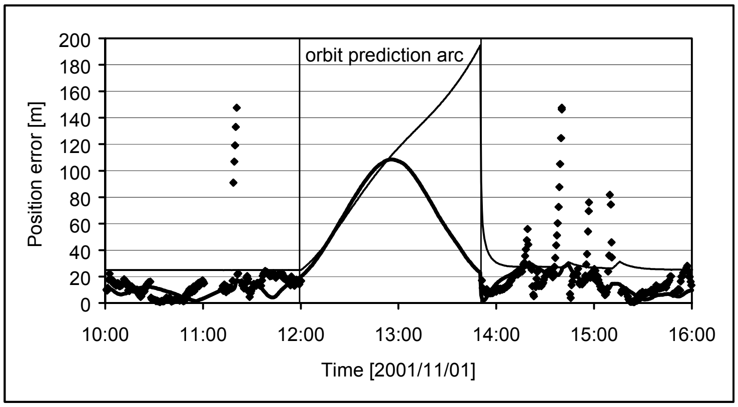

Fig. 5 Position error of the ONS within an orbit determination and orbit prediction arc. GEM-S measurement residuals are depicted by diamonds, while the ONS position solution and the associated position standard deviation is indicated by a bold and thin line, respectively.

Most interesting is the evolution of the ONS filter position error during its long time update phase. During the first 50 minutes an almost linearly increasing position error is observed, that closely matches the propagated standard deviation. Having reached a maximum error of 108 m it starts dropping again to a level of 25 m without any new measurements. Following the receivers reacquisition, the filter quickly reaches a stable performance at least within one hour.

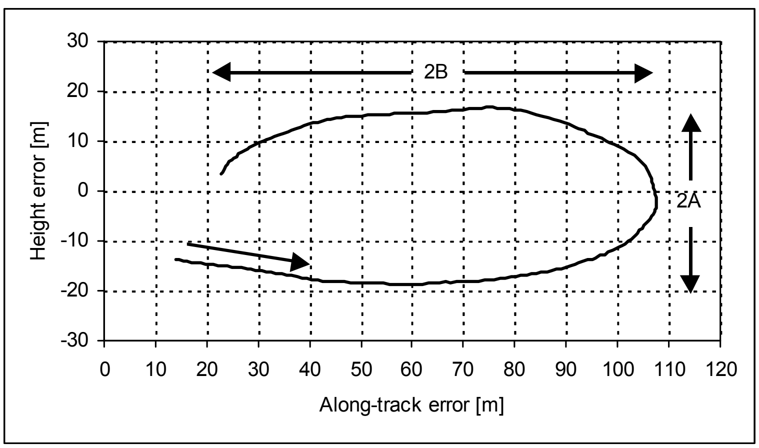

Fig. 6 ONS position error components during a prediction arc of about one orbital period.

At first sight, the drop of the ONS predicted position error within the second half of the prediction phase appears to be hardly explainable. However, an explanation is easily obtained by analyzing the orbital frame components of the total position error w.r.t. the reference orbit during the prediction period. The result is illustrated in Fig. 6 for a plane perpendicular to the cross-track direction, that almost completely covers the total position error observed, since cross-track errors are below 15 m during the prediction arc. As can be seen, the relative motion of the ONS filter w.r.t. the reference orbit follows closely an ellipse being offset from the origin in along-track direction by about 20 m. The ellipse's semi-major axis *B* is about 40 m and its semi-minor axis *A* is about 18 m.

The pattern observed in Fig. 6 is well known for a relative motion arising from velocity errors in radial direction [5]. At the time of the last measurement update of the Kalman filter, the ONS velocity error was dominated by the radial velocity error of about Δv_r = -2.0 cm/s. This leads to an ellipsoidal motion w.r.t. the reference trajectory, with a semi-major axis $B = 2 \cdot A$, while the semi-minor axis A is given as $\Delta v_r = A \cdot n$ [5], n being the satellite's mean motion. As applied to the case considered, a radial velocity error component of -2.0 cm/s implies a semi-minor axis A of 20 m, in close agreement to the observation of 18 m. Thus the maximum position error encountered appears at $T/2$, when it is governed almost completely by an along-track error of $2 \cdot B = 4 \cdot A$, or 80 m, again in close agreement to the observations.

CONCLUSIONS

Following a successful launch of the BIRD satellite on October 22, 2001 the first flight data from the Onboard Navigation System (ONS) have been obtained and analyzed. The ONS makes use of a low-cost GPS receiver to demonstrate autonomous navigation technologies onboard a small satellite. Based on a precise dynamical Kalman filter algorithm, the real-time provision of precise position and velocity data for the support of the satellite attitude control system is demonstrated as well as the geocoding of payload imagery on-the-flight.

The ONS has successfully been initialized and is now completely operational. Analysis of the accuracy provided by the GEM-S GPS receiver of Rockwell Collins shows an accuracy level of 10 m (rms) for the position and of 0.4 m/s (rms) for the velocity, close to the results from preflight hardware-in-the-loop simulations. Based on a dynamical filtering of the BIRD position solutions, the ONS delivers real-time position and velocity solutions of 5 m (rms) for position and 0.006 m/s (rms) for velocity, that improves the raw measurement performance by a factor of 2 and 50. Especially the improved velocity knowledge, gained from the ONS, provides a prerequisite for the ONS orbit prediction capabilities, which have been demonstrated to be as low as 110 m for a two hour forecast.

The smooth operations and the excellent performance of the ONS for BIRD renders its development a remarkable success and the experience gained boosts GSOC into a front row in the field of autonomous navigation.

ACKNOWLEDGEMENT

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